# Studies on Concrete Made of Recycled Aggregate Materials for Sustainability

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**Abstract -** The increasing demand for construction materials has led to the excessive consumption of natural resources and the generation of large volumes of construction and demolition waste. This has created serious environmental concerns, including resource depletion, landfill overflow, and increased carbon emissions. In this context, the use of recycled materials in concrete production has emerged as a sustainable and eco-friendly alternative. This study explores the potential of recycled aggregates and other waste materials such as plastic, glass, rubber, and industrial by-products in the development of sustainable concrete.

Recycled Concrete Aggregate (RCA), obtained from demolished structures, has been widely studied as a substitute for natural aggregates. The results indicate that concrete made with RCA can achieve satisfactory mechanical properties, including compressive strength and durability, when proper mix design and processing techniques are employed. Although the strength of recycled concrete may be slightly lower than conventional concrete, the difference is often within acceptable limits for many structural and non-structural applications. The addition of supplementary cementitious materials such as fly ash, silica fume, and ground granulated blast furnace slag further enhances the performance and durability of recycled concrete.

In addition to RCA, other waste materials have also shown promising results in concrete production. For instance, waste plastic can be used as a partial replacement for aggregates, resulting in lightweight and durable concrete. Similarly, crushed glass and rubber particles improve certain properties such as thermal insulation and flexibility. Industrial by-products not only reduce the need for cement but also decrease greenhouse gas emissions associated with cement manufacturing. These materials contribute to improved sustainability by reducing environmental pollution and promoting waste utilization.

From an environmental perspective, the use of recycled materials in concrete significantly reduces the carbon footprint of construction activities. It minimizes the extraction of natural aggregates, conserves energy, and reduces landfill waste. Life cycle assessment studies have demonstrated that recycled concrete can lower overall environmental impacts compared to conventional concrete. Furthermore, the concept aligns with the principles of the circular economy, where materials are reused and recycled to maintain their value for as long as possible.

Despite its advantages, the use of recycled materials in concrete presents certain challenges. These include variability in material quality, higher water absorption, reduced workability, and lack of standardized guidelines. Proper treatment methods, quality control measures, and advanced technologies are required to overcome these limitations. Research and development efforts are ongoing to improve the consistency and performance of recycled concrete.

In conclusion, concrete made from recycled materials offers a viable solution for sustainable construction. It not only addresses environmental issues but also supports resource conservation and waste management. With continued research, innovation, and policy support, recycled concrete has the potential to become a mainstream construction material in the future.

**Keywords**

Recycled concrete aggregate, sustainable construction, green concrete, waste materials, fly ash, silica fume, environmental impact, circular economy, durability, compressive strength

## 1. INTRODUCTION

### 1.1 Background and Motivation

Most engineering constructions are not eco-friendly. Construction industry uses Portland cement which is known to be a heavy contributor to the $CO_2$ emissions and environmental damage. In India, amount of construction has rapidly increased since last two decades. Using various types of supplementary cementing materials (SCMs), especially SF and FA, as a cement replacement could result in a substantial reduction of the overall $CO_2$ footprint of the final concrete product. Lesser the quantity of Portland cement used in concrete production, lesser will be the impact of the concrete industry on the environment.

The deposition of construction garbage which is increasingly accumulated due to various causes such as demolition of old construction is also an environmental concern [Topcu and Guncan 1995]. In India, the Central Pollution Control Board has assessed that the solid waste generation is about 48 million tonnes per annum of which 25% are from the construction industry. This scenario is not so different in the rest of the world. In order to decrease the construction waste, recycling of waste concrete as aggregate is beneficial and effective for preservation of natural resources [Khalaf and Venny 2004].

Usage of demolished concrete, SF and FA in construction industry is more holistic as it contributes to the ecological balance. However, use of these waste materials in construction industry especially in the making of concrete is highly challenging. Significant research efforts are required to study the engineering properties of concrete made of such industrial wastes. Present research is an effort to study the properties of concrete incorporating industrial wastes such as demolished concrete, SF and FA. Demolished concrete can be used as recycled coarse aggregate (RCA) to make new concrete (RCA concrete) by partially or fully replacing the natural coarse aggregate (NCA). Various researchers have examined the physical and mechanical properties of RCA concrete and found that the mechanical strength of the RCA concrete is lower than that of conventional concrete with NCA. This is due to the highly porous nature of the RCA compared to NCA and the amount of replacement of NCA [Rahal 2007]. The physical properties of the RCA depend on the amount of adhered mortar and its quality. Amount of adhered mortar depends on the process of crushing of parent concrete. Due to these reasons, RCA shows more porosity, more water absorption, low density and low strength as compared to the natural aggregate. Previous researchers reported that up to 25% reduction in compressive strength has been occurred due to above reasons [Amnon 2003; Elhakam *et al*. 2012; Tabsh and Abdelfatah 2009, McNeil and Kang 2013].

The relationship between the water-to-cement ($w/c$) ratio and the compressive strength is essential for the preliminary estimation of water and other constituent materials for mix design of concrete. Indian standard recommends such relationship for NCA concrete. This relationship may be different for RCA concrete depending on its age and number of recycling. Many studies [Rahal 2007; Amnon 2003; Tabsh and Abdelfatah 2009; Kou *et al*. 2011, Kou and poon 2009; and Padmini *et al*. 2009] are reported in literature that focuses on the behaviour, properties, and functional uses of RCA. However, no studies have been reported on the behaviour of RCA concrete with regard to above aspects. The present work is an attempt to study the relationship of w/c ratio with compressive strength considering age and number of recycling of RCA.

The rising tide of adoption of RCA for construction demands an investigation of methods to improve the quality of RCA concrete. Use of urease-producing bacteria can address the problems associated with RCA concrete to some extent. Such bacteria can precipitate $CaCO_3$ through urease activity [Pei *et al*. 2013; Pacheco-Torgal and Labrincha 2013; and Siddique and Chahal 2011] which catalyzes the hydrolysis of urea into ammonium and carbonate. First, urea is hydrolyzed intracellular to carbamate and ammonia. Carbamate spontaneously hydrolyzes to form additional ammonia and carbonic acid. These products subsequently form bicarbonate, ammonium, and hydroxide ions. These reactions increase the ambient pH, which in turn shifts the bicarbonate equilibrium, resulting in the formation of carbonate ions. This leads to accumulation of insoluble $CaCO_3$, which fills up the pores of the concrete and improves the impermeability and strength. Bacterial calcium carbonate mineralization using urease producing bacteria is proposed in the present study to improve the quality of RCA concrete.

Like all other pozzolanic materials, SF is capable of reacting with the calcium hydroxide, $Ca(OH)_2$ liberated during cement hydration to produce hydrated calcium silicate (C–S– H), which is accountable for the strength of hardened concrete. The high content of very fine amorphous spherical (100 nm average diameter) silicon dioxide particles (present more than 80%) is the main reason for high pozzolanic activity of SF. The SF can improve both chemical and physical properties, which transform the microstructure of concrete and hence reduce the permeability and increase the strength. Most of the previous studies on the SF concrete are conducted using Portland cement for high strength concrete applications. International codes [ACI 234R-96] recommend an additional 10% of cement when SF is used as partial replacement of cement in the construction practice. The mechanical properties of SF concrete considering the 10% additional quantity of cement as recommended by international codes, incorporating slag cement on low to medium strength concrete, have not been investigated so far. The present study investigates the mechanical properties of medium strength SF concrete made as per this construction practice using slag cement.

Randomness and variability of material properties can considerably affect structural performance and safety. In contradiction to reality this phenomenon is usually neglected, in conventional structural analysis and design that assume deterministic values of material properties. This assumption makes the analysis models less realistic and less satisfactory. With the advancement of computing facilities, the complex structural analyses including the probabilistic nature of the various parameters of the structure are not difficult and have become essential for its response against natural loads like earthquake, wind, etc. There are many studies [Campbell and Tobin 1967; Soroka 1968; Chmielewski and Konapka 1999; and Graybeal and Davis 2008] reported on the variability of compressive strength of concrete. The variability of compressive strength of concrete usually represented in literatures by a normal distribution if the coefficient of variation does not exceed 15-20%, although slight skewness may be present. However, when the coefficient of variation is high, the skewness is considerable [Campbell and Tobin 1967] and if the quality control is poor [Soroka 1968], a lognormal distribution is more rational to represent the tail areas of distribution than a normal distribution. A recent study [Chen *et al*. 2014] concludes that the variation in concrete compressive strength should be characterized using various statistical criteria and different distribution functions. The inherent variability of cement and SF may not be similar in nature, as SF is a by- product in the carbothermic reduction of high-purity quartz with carbonaceous materials like coal, coke, wood-chips in the production of silicon and ferrosilicon alloys. Therefore, existing literatures on the variability of cement concrete may not be useful to describe the variability of concrete with SF. One of the focuses of the present study is to describe the variability of concrete using SF by finding out a best fitted probability distribution matching the experimental data. An attempt has been made to study the seismic behaviour of typical RC structures through fragility analysis considering the variability of the SF concrete obtained from experiments.

FA, which is another material used to supplement cement popularly to produce concrete. A part of the present study is devoted to investigate the above-described properties for FA concrete also.

## 1.2 Objectives

Based on a detailed literature review (presented in Chapter 2), the major objective of the present research work is identified as the investigation of properties of concrete made using various alternative materials (RCA, SF and FA) and its possible enhancement. Following are the sub-objectives to achieve the major goal.

i. To study the relationship of *w/c* ratio and compressive strength, the effects of age and number of recycling on the properties of RCA concrete.
ii. To study the enhancement of engineering properties of RCA concrete using bacteria.
iii. To investigate the mechanical properties of low to medium strength SF concrete incorporated with 10% additional cement quantity as per the construction practice.
iv. To describe the variability in the properties of both SF and FA concrete and its implications in the seismic behavior of typical building structures through fragility analysis.

## 1.3 Scope

Following are the scopes and limitations of the present study

1. Present construction industry uses slag cement over ordinary Portland cement. 90% of the cement used in Indian construction industry are of slag cements. Present research, therefore, considers only slag cement for all the studies.
2. Only low to medium strength concrete are considered in the present study as the usage of this type of concrete is higher compared to high strength concrete.
3. Only two parameter probability distributions are considered for the description of variability of SF and FA concrete.
4. Only three statistical goodness of tests such as Kolmogorov-Sminrov, Chi-square and log-likelihood tests are used for evaluation of best –fit probability distribution models.

## 2. Literature Review

Crushed concrete that results from the demolition of old structures is generated nowadays in large quantities. The current annual rate of generation of construction waste is 145 million tonnes worldwide [**Revathi *et al.* 2013**]. The area required for land-filling this amount of waste is enormous. Therefore, recycling of construction waste is vital, both to reduce the amount of open land needed for land-filling and to preserve the environment through resource conservation [Revathi *et al.* 2013, **Pacheco-Torgal *et al.* 2013**]. It has been widely reported that recycling reduces energy consumption, pollution, global warming, greenhouse gas emission as well as cost [Khalaf and Venny 2004; Pacheco-Torgal and Said 2011; Ameri and Behnood 2012; Vázquez 2013; **Behnood *et al.* 2015**; Pepe 2015 and Behnood *et al.* 2015]. This in turn is beneficial and effective for environmental preservation

Various researchers have examined about the physical and mechanical properties of the RCA and its influence when natural aggregate is replaced partially or fully by RCA to make concrete. It has been found that the mechanical strength of the RCA concrete is lower than that of conventional concrete. This is due to the highly porous nature of the RCA compared to natural aggregates and the amount of replacement against the natural aggregate [**Rahal 2007, Brito and Saikia 2013**].

The physical properties of the RCA depend mainly on the adhered mortar and generally RCA shows more porosity, more water absorption, low density and low strength as compared to the natural aggregate concrete. It is reported that up to 25% reduction in compressive strength has been occurred due to above reasons [Amnon 2003; Tabsh and **Abdel fatah 2009; El hakam *et al.* 2012**; McNeil and Kang 2013].

**Bar budo *et al.* (2013)** studied the influence of the water reducing admixture on the mechanical performance of the recycled concrete. This study shows that use of plasticizers may improve the properties of recycled concrete. Rahal (2007) investigated the mechanical properties of recycled aggregate concrete in comparison with natural aggregate concrete.

**Tabsh and Abdelfatah (2009)** studied the behavior of recycled aggregate and their mechanical properties. It is reported that the strength of recycled concrete can be 10–25% lower than that of natural aggregate concrete. It is reported that though the recycled aggregate is inferior to natural aggregate, their properties can be considered to be within the acceptable limits.

**Kou *et al.* (2011)** investigated the long-term mechanical properties and pore size distribution of the recycled aggregate concrete. It is reported that after 5 years of curing, the recycled aggregate concrete had lower compressive strength and higher splitting tensile strength than that of the natural aggregate concrete.

**Kou and Poon (2009)** studied the self-compacting concrete made from both recycled coarse and fine recycled aggregate. The different tests covering fresh, hardened and durability properties were investigated and the results show that both fine and coarse recycled aggregates can be used in self-compacting concrete. The similar observation was also made by **Grdic *et al.* (2010).**

**Li (2009)** has developed mix design for pervious recycled concrete with compressive strength and water seepage velocity as verification indexes. The Volume of voids is also tested for feasibility of new proposed mix design. **Fathifazl *et al.* (2009)** proposed a new method of mixture proportioning for concrete made with coarse recycled concrete aggregates. The new method was named as "equivalent mortar volume" in which the total mortar volume was kept constant.

**Bairagi *et al.* (1990)** proposed a method of mix design for recycled aggregate concrete from the available conventional methods. It has been suggested that the cement required was about 10% more in view of the inferior quality aggregate.

The adhered mortar forms a weak porous interface, which influences the strength and performance of RCA concrete [Ollivier *et al.* 1995; Prokopski and Halbi niak 2000; and Tam *et al*. 2005] and subsequently results in concrete with lower quality [Mehta and **Aitcin 1990; Bentz and Garboczi 1991**; Aitcin and Neville 1993; Alexander, 1996; Buch *et al.* 2000; Kwan *et al.* 1999]. This is considered to be one of the most significant differences between RCA and NCA concrete.

It has been reported that concrete made with 100% recycled aggregates is weaker than concrete made with natural aggregates at the same water to cement ratio (*w*/*c*) and same cement type. Many published literature [Amnon, 2003; Tabsh and Abdelfatah, 2009; **Elhakam *et al.* 2012 and McNeil and Kang, 2013**] reported that RCA concrete with no NCA reduces the compressive strength by a maximum of 25% in comparison with NCA concrete. A similar trend was observed in the case of tensile splitting strength and flexural strength [Silva *et al*. 2015].

**Wardeh *et al.* (2014)** carried out an experimental program on RCA concrete according to

the mix design method given in Eurocode 2. Sriravindrarajah *et al.* (2012) proposed a mix design for pervious concrete and developed an empirical relationship between porosity, compressive strength and water permeability. Brito and Alves (2010) studied the correlation of mechanical properties, density and water absorption of RCA concrete.
**Lauritzen (1993) and Dhir *et al.* (1999)** reported that RCA concrete requires more water for the same workability as compared to NCA concrete. Hansen, 1986; found that density, compressive strength and modulus of elasticity of RCA concrete are relatively lesser than that of the parent concrete. RCA concrete results in higher permeability, rate of carbonation and risk of reinforcement corrosion than NCA concrete for a given w/c ratio.
**Gayarre *et al.* (2015)** studied the variation of w/c ratio of some mechanical properties of concrete. The results showed a significant decrease in mechanical properties with an increase of *w*/*c* ratio when natural aggregates are completely replaced by recycled aggregates. Gayarre *et al.* (2014) investigated the effect of different curing conditions on the compressive strength of RCA concrete and showed compressive strength of RCA concrete is reduced up to 20% when cured in open-air conditions.

There are several techniques available in the literature [Achtemichuk 2009; Berndt 2009; González-Fonteboa *et al.* 2009; Kou and Poon 2012 and Limbachiya *et al.* 2012] to enhance the properties of RCA concrete such as partial replacement of cement with SF and FA, addition of nanoparticles, etc. However, use of bacteria to enhance the properties of RCA concrete is not attempted by any previous researchers. Similar studies on NCA concrete are also found to be very limited.

# 3. Methodology and Results

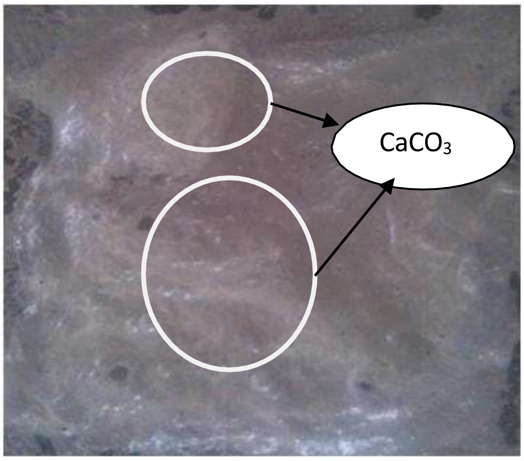
## 3.1.1 Experimental Results

Compressive strength, drying shrinkage and capillary water absorption test of hardened concrete and air content test of fresh concrete were carried out for all the concrete samples listed in previous section. Three samples were tested for each category and the average of the three was considered as the final result. Following sections discuss the results obtained from these tests.

### 3.1.1.1 *Compressive Strength*

The addition of bacteria to the fresh concrete results in the formation of $CaCO_3$ precipitation that can be observed through the naked eye as shown in Fig. 3.9. Fig. 3.9 presents photographs of typical RCA concrete with *B. Subtilis* and *B. sphaericus* ($10^6$ cells/ml), RCA control and NCA concrete without bacteria. White foam like material can be visualised in the outer surface of the bacterial concrete sample (Figs. 3.9a and 3.9b) which are absent in other two (Figs. 3.9c and 3.9d).

The mean compressive strength for specimens with different concentration of bacteria at 7 days and 28 days are presented in Table 3.14. It is observed that the compressive strength of bacterial concrete increases with the increase of cell concentration for both 7 days and 28 days strength. However, after cell concentration of $10^6$ cells/ml the trend reverses. The same results are plotted in Figs. 3.10 and 3.11 for *B. subtilis* and *B. sphaericus*. The maximum increment of 28 days compressive strength of RCA concrete is found to be 20.93% for *B. Subtilis* (B-3a) and 35.87% for *B. sphaericus* (B-3b) with respect to RCA control mix with an optimum cell concentration of $10^6$ cells/ml. The same trend is also reported for bacterial NCA concrete in the literature [Chahal *et al.* 2012a, 2012b]. This increase of compressive strength may be due to the precipitation of $CaCO_3$ by bacteria on the micro-organism cell surfaces and within the inner side of the concrete which is confirmed in the microstructure analysis (refer section 3.4.3.5 and 3.4.3.6). The compressive strength is improved by the microbiological precipitation of $CaCO_3$ in the micro pores of concrete. Since the cell concentration of $10^6$ cells/ml yields maximum compressive strength of RCA concrete the further investigation on bacterial concrete are conducted only considering this cell concentration for both the two selected bacteria (B-3a and B-3b).



(a) RCA concrete with *B. subtilis* (B-3a)

(b) RCA concrete with *B. sphaericus* (B-3b)

(c) RCA concrete without bacteria (Control)

(d) NCA concrete without bacteria

Figure 3.9: Photographs of fresh concrete specimens

Table 3.15: Effect of bacteria on compressive strength (MPa) at 7 & 28 days

| Mixture Name | 7 days | | 28 days | |
|---|---|---|---|---|
| | *B. subtilis* | *B. sphaericus* | *B. subtilis* | *B. sphaericus* |
| NCA (0 cells/ml) | 33.15 | 33.15 | 44.08 | 44.08 |
| Control (0 cells/ml) | 29.06 | 29.06 | 38.22 | 38.22 |
| B-1 ($10^1$cells/ml) | 31.27 | 30.13 | 41.02 | 43.10 |
| B-2 ($10^3$cells/ml) | 32.70 | 33.59 | 43.13 | 46.71 |
| B-3 ($10^6$cells/ml) | 34.15 | 38.86 | 46.22 | 51.93 |
| B-4 ($10^7$ cells/ml) | 32.80 | 34.64 | 44.60 | 48.55 |

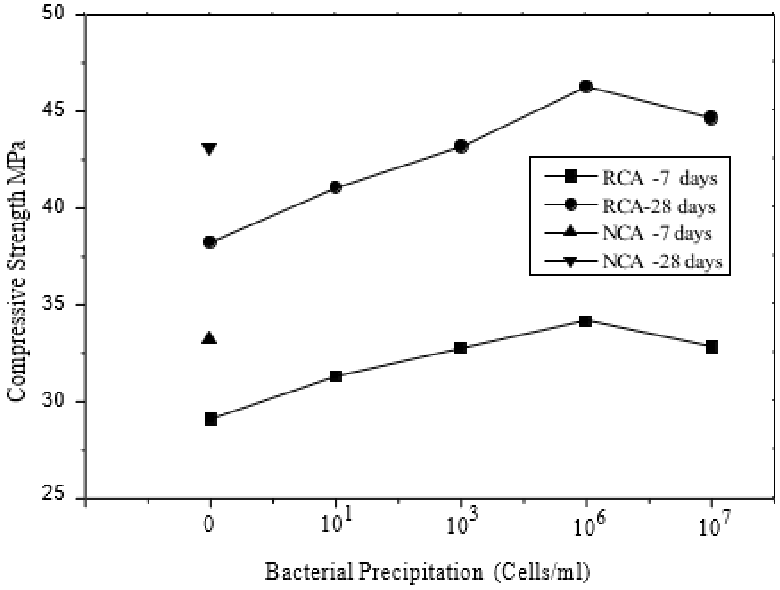


Figure 3.10: Effect of *B. subtilis* on compressive strength

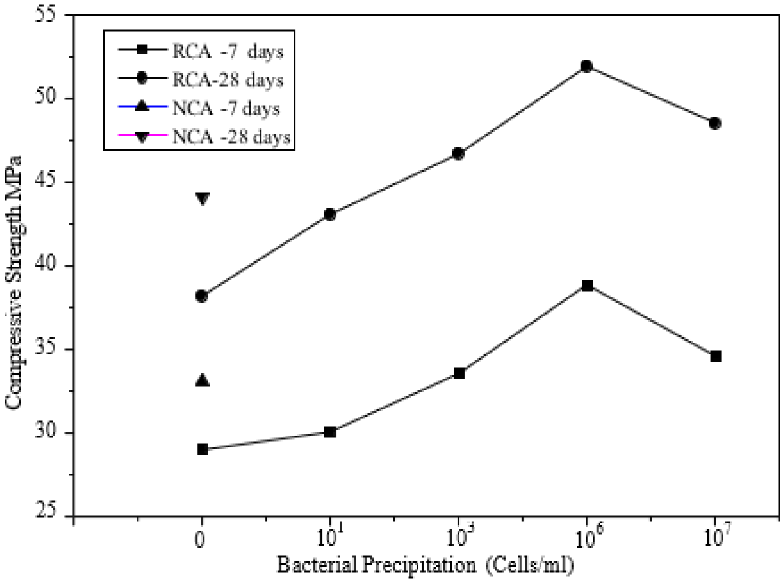


Figure 3.11: Effect of *B. sphaericus* on compressive strength

### 3.1.1.2 *Drying Shrinkage*

Drying shrinkage of the concrete specimen is measured after 28 days curing including 7 days moist air curing. The drying length and drying shrinkage obtained for four specimens, NCA, RCA Control, B-3a and

B-3b are tabulated in Table 3.15. It is noticed that the addition of bacteria to RCA concrete decreases the drying shrinkage. This can be attributed to denser RCA concrete formed by bacterial activity. It is to be noted that the drying shrinkage of RCA control concrete is more than that of NCA concrete. Similar observations are also reported in previous literature [Kou and Poon 2009; Manzi et al. 2013; Jose and Soberon 2002; and Eguchi *et al*. 2007]. The increase of drying shrinkage of RCA control concrete without bacteria is perhaps due to the shrinking of old mortar adhered to the surface of RCA. However, previous studies [Kou and Poon 2012; Kou and Poon 2009] show that it can be controlled by reducing the *w*/*c* ratio suitably. Another cause for higher drying shrinkage of RCA control concrete maybe its low elastic modulus, as compared to NCA concrete, which offer less restraint to the potential shrinkage.

Table 3.16: Drying shrinkage of the concrete specimens

| Type of Concrete | Drying Length (mm) | Drying Shrinkage (%) |
|---|---|---|
| NCA | 0.135 | 0.09 |
| RCA Control | 0.260 | 0.17 |
| B-3a (*B. subtilis*) | 0.040 | 0.03 |
| B-3b (*B. sphaericus*) | 0.090 | 0.06 |

### 3.1.1.3 *Air Content*

Table 3.16 shows the results of air content in the four samples, NCA, RCA control, B-3a and B-3b. Air content of both the bacterial concrete samples are found to be slightly more than the RCA control concrete, probably due to the bacterial activity (such as photosynthesis, etc.). The air content of bacterial concrete may be reduced by increasing the mixing time to allow the extra air to flow out of the concrete mix.

Table 3.17: Air content of freshly mixed concrete

| Type of Concrete | Air Content (%) |
|---|---|
| NCA | 12 |
| RCA Control | 12 |
| B-3a (*B. Subtilis*) | 13 |
| B-3b (*B. Sphaericus*) | 13 |

### 3.1.1.4 *Capillary Water Absorption*

The capillary water absorption of selected specimens are tested and presented in Fig. 3.12. The slope of these curves is decreasing in nature; similar behaviour was observed in previous studies [Bai and Sabir 2002; and Hanžič and Ilić 2003]. The water absorption for RCA samples (control, B-3a and B-3b) is higher than NCA samples, which is due to the additional water absorbed by the old mortar adhered to RCA. Capillary water absorption of bacterial concrete sample (B-3a and B-3b) is less than that of RCA control specimen. This is attributed to the denser concrete formed by bacterial precipitation of $CaCO_3$.

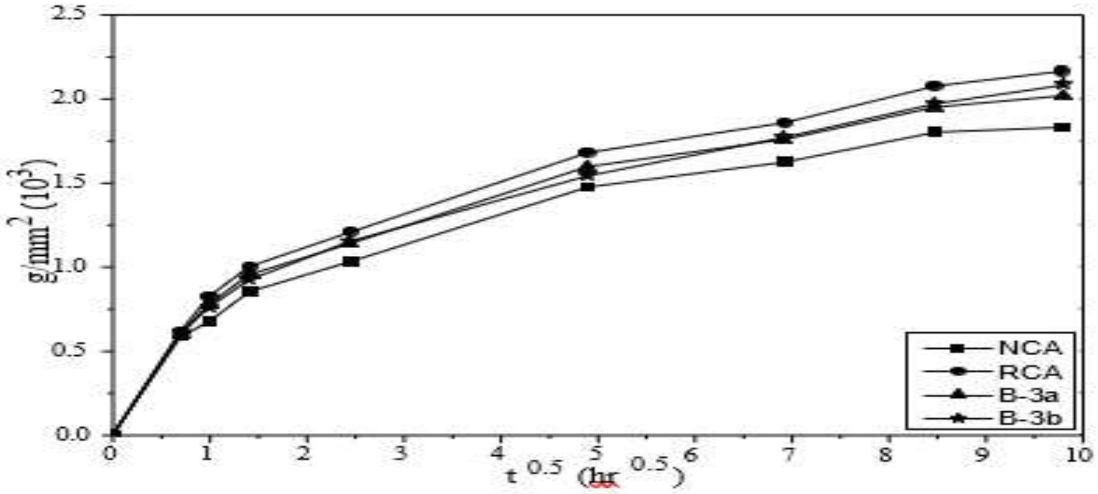


Figure 3.12: Variation of capillary water absorption

### 3.1.1.5 *SEM and EDX*

Both the bacterial concrete samples (B-3a and B-3b) and RCA control specimen are examined through SEM, and the results are presented in Figs. 3.13-3.15. Deposition of calcium carbonate as calcite in both the bacterial concrete samples (B-3a and B-3b) is observed through SEM. More crystalline calcium carbonate is observed in the pores of bacterial concrete than RCA control concrete. Fig. 3.16 shows the intensities of various compounds from EDX at a point in the region marked in the Fig. 3.13. The intensities of various compounds indicate the presence of calcite precipitated in the form of calcium carbonate.

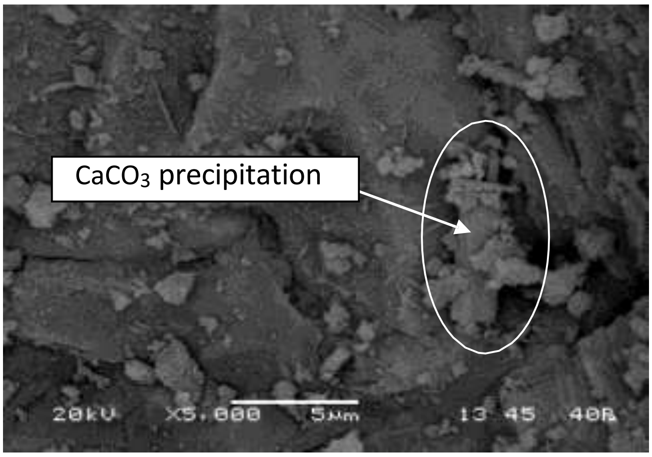


Figure.3.13: SEM of B-3a concrete sample

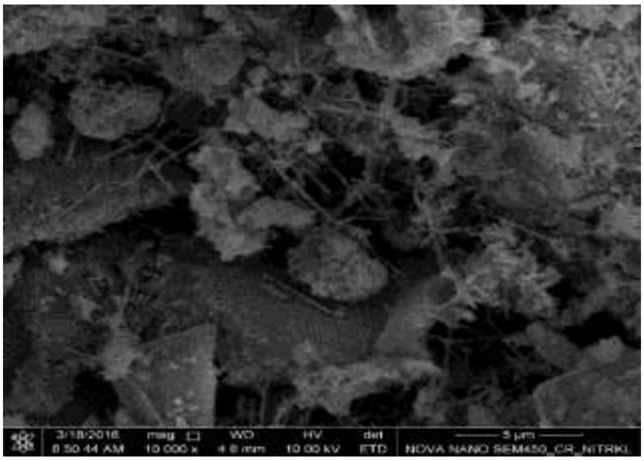


Figure 3.14: SEM of B-3b concrete sample

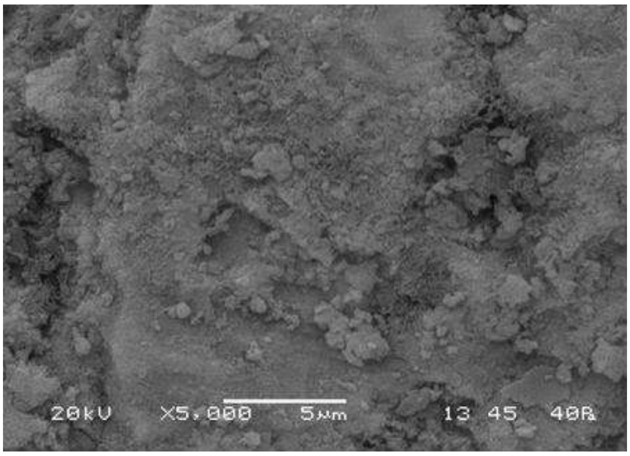


Figure 3.15: SEM of RCA control mix

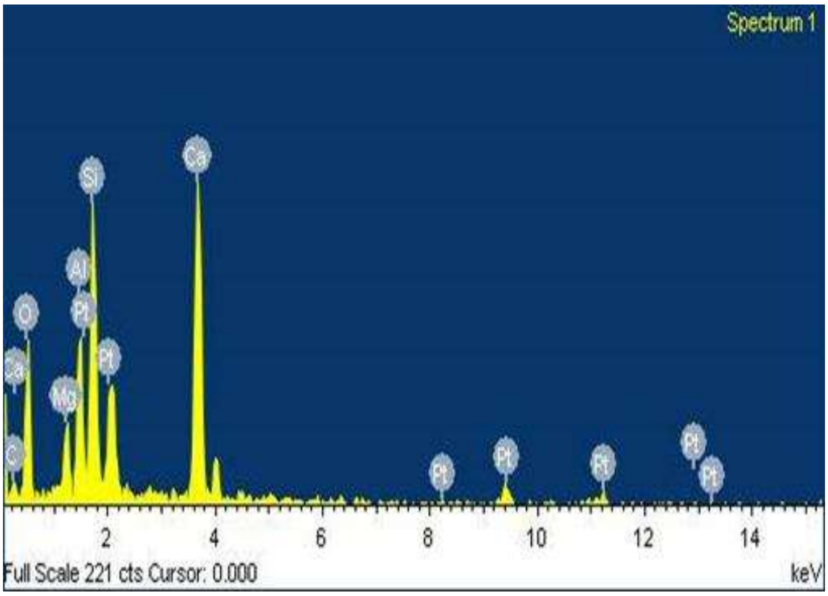
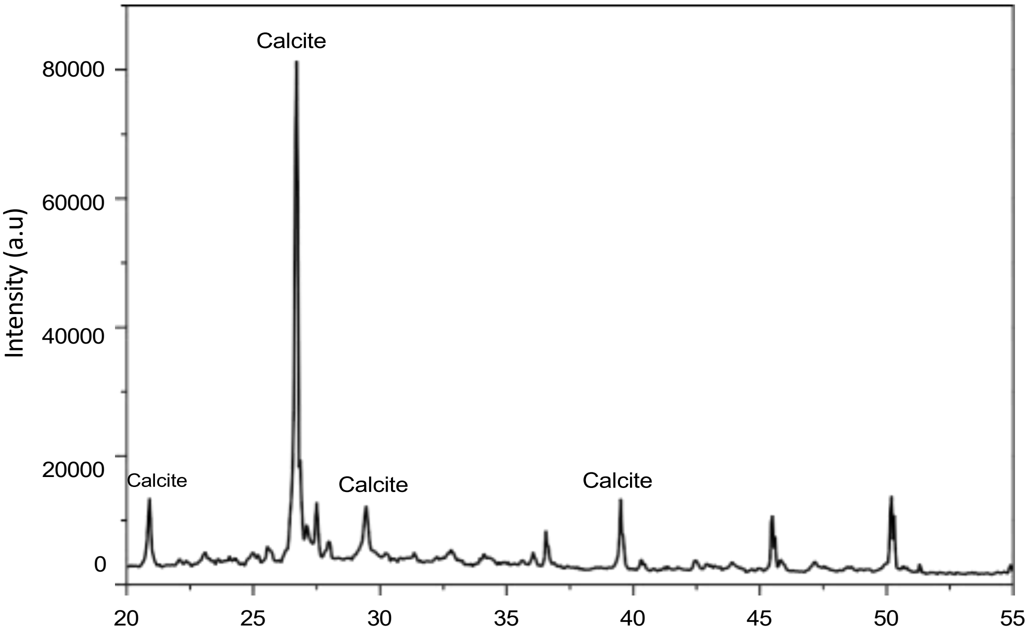


Figure 3.16: EDX of B-3a sample concrete at marked outlines

### 3.1.1.6 *XRD Spectroscopy*

The results of the XRD of both the bacterial concrete samples (B-3a and B-3b) and RCA control specimen are presented in Figs. 3.17-3.19. It can be seen that more calcite is precipitated with higher intensity in bacterial concrete. Also, it has been seen that in the case of bacterial concrete, calcite is precipitated in more crystalline form.



2θ Degree

Figure 3.17: XRD analysis of B-3a concrete

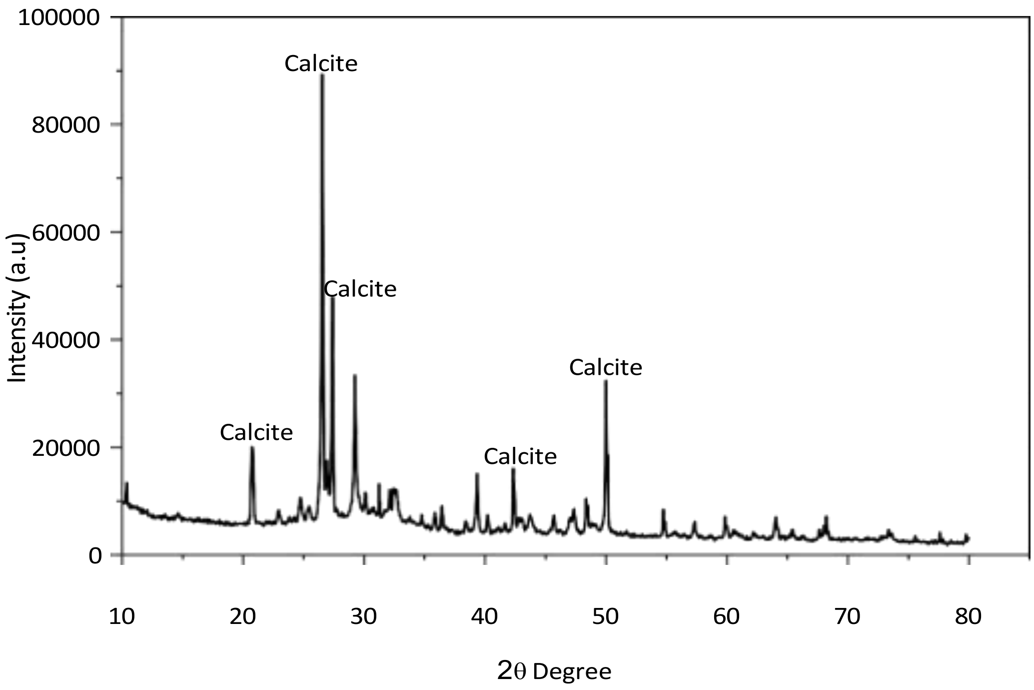


Figure 3.18: XRD analysis of B-3b concrete

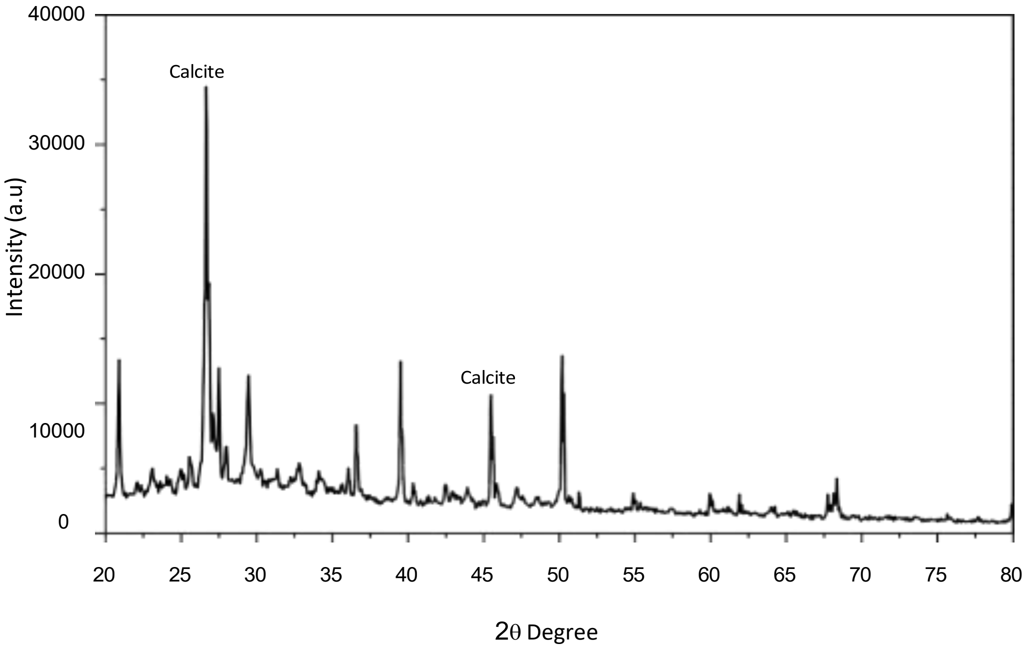


Figure. 3.19: XRD analysis of RCA control

## 3.2 Cement Mortar using Ureolytic Bacteria

Aggregate is the main source of dispersion for strength of concrete. Also, it does not take part in the mineral precipitation by the bacteria. Accordingly, the purpose of this section is to study the effect of bio-mineralization on the cement-based product avoiding the problems associated with the variation of aggregate properties. Accordingly, the effect of bacteria on some specific properties of cement, such as standard consistency and setting time, and properties of cement mortar such as compressive strength, sorptivity need to be investigated for more clarity. Published literature on the effect of bacteria on the above-mentioned aspects are limited. This section discussed the study of cement and cement mortar incorporating *B. sphaericus*. Culture and growth of *B. sphaericus* for this part of work are carried out like the methods discussed in the section 3.3.1. The specifications of materials, Portland slag cement and fine aggregate, used for this study are explained in section 3.2.1

### 3.2.1 Effect of Bacteria on the Properties of Fresh Cement Mortar

Standard tests on cement is conducted for the consistency of cement as per Indian standard IS 4031 Part 4 (1988). The consistency of the cement paste is found to be 32%. In order to check the effect of bacteria in the initial and final setting time of cement, standard tests for setting time are conducted on cement mortar as per Indian standard IS 455 (1989).

Previous literature on the influence of bacteria in the setting time are very limited. No study has been reported on the initial and final setting time of cement by using *B. sphaericus*. Initial and final setting time of cement paste with and without bacteria are found out and presented in Table 3.17. Initial setting time of mortar with the inclusion of bacteria is 50 minutes which is marginally lower than the normal mortar (52 minutes). Similarly, final setting time of mortar with bacteria is 6 Hrs 07 Minutes while for normal mortar, it is 6 Hrs 00 Minutes. The effect of bacteria on the setting time is found to be very negligible.

Table 3.18: Comparison of setting time of cement

| Specimen | Initial Setting time (minutes) | Final Setting time |
|---|---|---|
| Cement paste (Normal) | 52 | 6 Hrs. 00 Minutes |
| Cement paste (With bacteria) | 50 | 6 Hrs. 07 Minutes |

### 3.2.2 Effect of Bacteria on the Properties of Harden Cement Mortar

The variation of compressive strength of mortar cubes with different concentrations of *B. sphaericus* are studied. Cement to sand ratio of 1:6 and water cement ratio of 0.55 are considered to prepare the mortar cubes. Accordingly, the amount of cement, sand and water are calculated as shown in the Table 3.18. Mortar cubes are prepared by mixing the water containing cell culture in selected concentrations, with the cement and sand. This mortar cubes are referred in this study as bacterial mortar cubes. The bacterial mortar cubes are represented by prefix 'B' as shown in Table 3.18. Bacterial cubes are cured in 2% urea (in water) and 25mM $CaCl_2$ per ml of curing water. Mortar cubes without bacteria is referred as control cube specimens. Control cubes, denoted as CT (refer Table 3.17) are cured with normal tap water. In order to study the effect of curing medium on control specimen a set control cubes are cured using 2% urea and 25mM $CaCl_2$ per ml of curing water. This set is referred as CUC (mortar cured with urea). Cubes are casted in triplicates and compacted in a vibration machine. After demoulding, all specimens are cured until the testing.

#### 3.2.2.1 *Variation of Compressive Strength with Cell Concentration*

The cubes are tested in a load controlled universal testing machine to obtain the compressive strength at 7 days and 28 days. The compressive strengths of all the specimens are presented in Table 3.19. It can be observed from the table that as the cell concentration increases the compressive strength at both 7 days and 28 days increases initially and then decreases. It can be seen that the maximum percentage increase in compressive strength of about 58% is observed (at 7 days) in the mortar cube having a cell concentration of $10^7 cells/ml$. The variation of the compressive strength at 7-day and 28-day is also expressed graphically in Fig. 3.20. The maximum strength at 28 days is about 23% over the control specimen and this occurs at a cell concentration of about $10^7 cells/ml$ and hence this cell concentration can be treated as optimum dosage to obtain maximum compressive strength.

Table 3.19: Casting details of mortar cubes for compressive strength and sportively test

| Mortar cube ID | Bacteria concentration n (cells/ml) | Number of specimens for | | | Mix proportion | | | Curing medium |
|---|---|---|---|---|---|---|---|---|
| | | 7 days strength | 28 days strength | Sorptivity test | Cement (kg) | Sand (kg) | Water (*ml*) | |
| CT | 0 | 3 | 3 | 3 | 0.13 | 0.77 | 72 | † |
| CUC | 0 | - | 3 | - | 0.13 | 0.77 | 72 | Ø |
| B1 | $10^5$ | 3 | 3 | 3 | 0.13 | 0.77 | 72* | Ø |
| B2 | $10^6$ | 3 | 3 | 3 | 0.13 | 0.77 | 72 * | Ø |
| B3 | $10^7$ | 3 | 3 | 3 | 0.13 | 0.77 | 72 * | Ø |
| B4 | $10^8$ | 3 | 3 | 3 | 0.13 | 0.77 | 72 * | Ø |
| B5 | $10^9$ | 3 | 3 | 3 | 0.13 | 0.77 | 72 * | Ø |

* Indicates that the volume of water including bacteria and culture medium
† Indicates tap water as curing solution
Ø indicates a mix of tap water, urea and calcium chloride as curing solution

Maximum percentage increase in compressive strength in a previous study shows similar results. Ghosh *et al.* (2005) reported that maximum improvement in compressive strength of mortar at 28 days is about 25% with $10^5$*cells/ml* by using *Bacillus pasteurii*. Achal *et al.* (2011) had reported increase in compressive strength of mortar cube incorporating *B. sphaericus* to be about 23% and 36% at 7days and 28 days respectively. An increase of about 18% in strength of mortar with *B. pasteurii* at 28 days is reported by Ramachandran *et al.* (2001). Ramachandran *et al.* (2001) found that in initial days of curing, bacteria show good nourishment due to filling of pores mortar cubes by microbiologically induced mineral precipitation.

The compressive strength at 28 days of the specimen CUC (urea cured) is found to be about 5.67MPa. The compressive strength of CT specimen, cured with normal tap water at 28 days is about 5.9MPa. The change in compressive strength due to curing solution is found to be negligible. Negligible difference in compressive strength implies that curing solution alone has no significant effect on the specimen. The increase in compressive strength in other bacterial specimens (B1, B2, B3, B4 and B5) are due to the bacterial activity in the presence of (2% urea and 25mM $CaCl_2$ per ml of curing water) curing solution.

Table 3.20: Compressive strength of mortar cubes with different bacteria concentrations

| Mortar cube ID | Cell concentration (cells/*ml*) | Mean compressive strength (% increase) at 7 days (MPa) | Mean compressive strength (% increase) at 28 days (MPa) | Remark |
|---|---|---|---|---|
| CT | 0 (Control) | 3.44 | 5.90 | |
| CUC | 0 (Control) | 3.01 (-14%) | 5.67 (-4%) | |
| B1 | $10^5$ | 4.46 (29.70%) | 6.98 (18.30%) | |
| B2 | $10^6$ | 5.34 (55.23%) | 7.02 (18.98%) | |
| B3 | $10^7$ | 5.44 (58.23%) | 7.28 (23.38%) | Maximum |
| B4 | $10^8$ | 4.91 (42.73%) | 6.19 (4.90%) | |
| B5 | $10^9$ | 4.71 (36.90%) | 6.10 (3.38%) | |

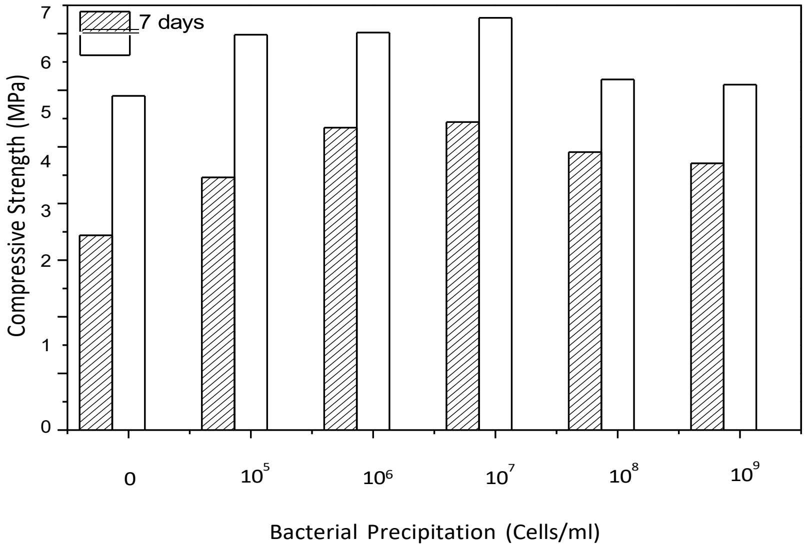


Figure 3.20: Variation of compressive strength with cell concentration – at 7 and 28 days

### 3.2.2.2 *Sorptivity*

Sorptivity test is conducted for both control and all bacterial specimens (B1, B2, B3, B4 and B5). The casting details of the specimens are provided in Table 3.20. The cumulative water absorption versus square root of time in hours (√t) for all bacterial specimens are computed as shown in Fig. 3.21. For durability point of view, sorptivity coefficient should be minimum. Sorptivity coefficient, $S$ (mm/h$^{0.5}$), slope (Gonen and Yazicioglu, 2007) of the trend lines, for all the specimens are found out from Fig. 3.21 and they are listed in Table 3.20. It can be seen that sorptivity coefficient is minimum (0.79) for B3, where bacteria concentration is about $10^7$ cells/ml. The lesser values of sorptivity coefficient imply that concrete is denser. This may be due to sealing of the pores by carbonation which in turn increase durability. Similar observations are also reported elsewhere (Gonen and Yazicioglu, 2007).

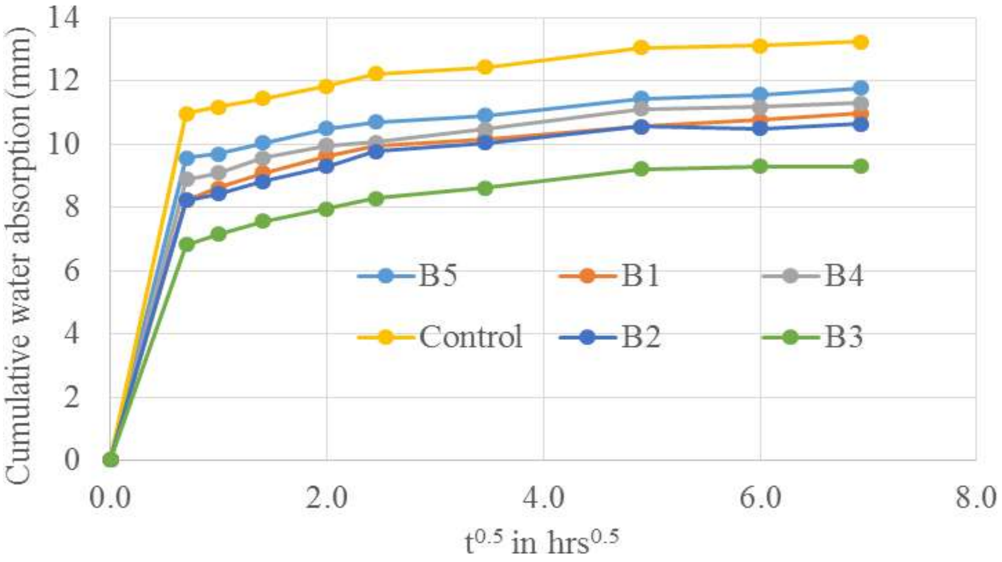


Figure 3.21: Cumulative water absorption for various cell concentrations Table 3.21: Sorptivity coefficients of all

specimens

| Specimen ID | Bacterial conc. (cell/ml) | Sorptivity coefficient, S | Compressive strength (MPa) |
|---|---|---|---|
| Control | 0 | 1.00 | 5.67 |
| B1 | $10^5$ | 0.89 | 6.98 |
| B2 | $10^6$ | 0.86 | 7.02 |
| B3 | $10^7$ | 0.79 | 7.28 |
| B4 | $10^8$ | 0.90 | 6.19 |
| B5 | $10^9$ | 0.90 | 6.10 |

### 3.2.2.3 *XRD Spectrometry*

The addition of bacteria into the mortar cubes resulted in the formation of calcite crystals. XRD is used to quantify the intensity of various compounds present in both bacterial and control specimens. Fig. 3.22 shows the results of the XRD and it can be seen that the number of calcite peaks (9 numbers of ‘C’) are more in bacterial mortar cube samples and less in control sample (4 numbers of ‘C’). The increase in number of peaks signifies that the presence of calcite is more in bacterial cubes than in control cubes. The sharp peaks of the XRD analysis indicate the crystallinity of the calcium carbonate. Similar conclusions are also reported elsewhere (Chahal *et al.* 2012). This increase in calcite content is perhaps responsible for the increase in compressive strength of bacterial mortar cubes.

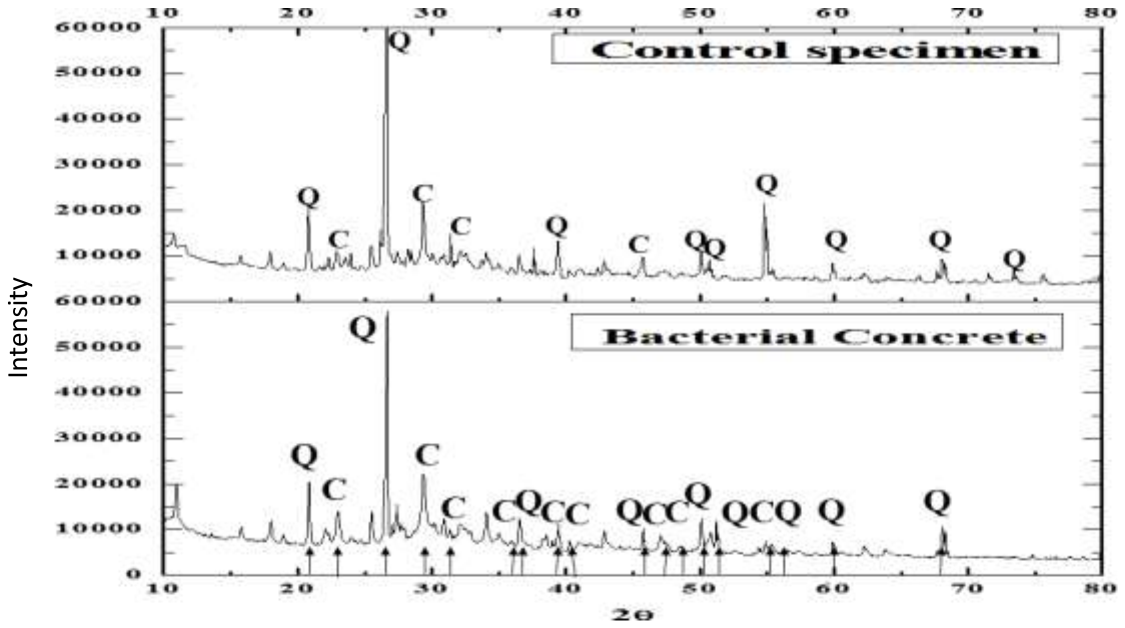


Figure 3.22: XRD of bacteria and control mortar cubes (‘Q’ represents quartz or silica and ‘C’ represents calcite).

### 3.2.2.4 *FESEM*

Fig. 3.23 shows rod shaped impression which is consistent with the shape of *B. sphaericus* (Siddique and Chahal. 2011). While, Fig. 3.24 shows the FESEM images of samples from control and bacterial specimen (B4) for 7 days of curing. Fig. 3.25 shows the images of the same samples for 28 days curing. The white patches of calcite crystals can be observed in these images and it is found that the amount of calcite crystals is more in the bacterial samples than in the control samples. The presence of the crystalline calcite may be the reason for the improvement of compressive strength.

In order to check the continuous variation in the microstructure of the cement mortar due to the presence of bacterial calcite precipitation, analysis of FESEM at 7, 14 and 28 days are carried out. Figs. 3.26(a) - 3.26(c) show the FESEM images of bacterial mortar cubes (B4) after 7, 14 and 28 days of curing respectively. It is observed that needle shaped structures are seen more in concentration and their number increases with number of days of curing and are less when it reaches a curing period of 28 days. Concentration of Lamellar rhombohedra structures increases as the curing period increases.

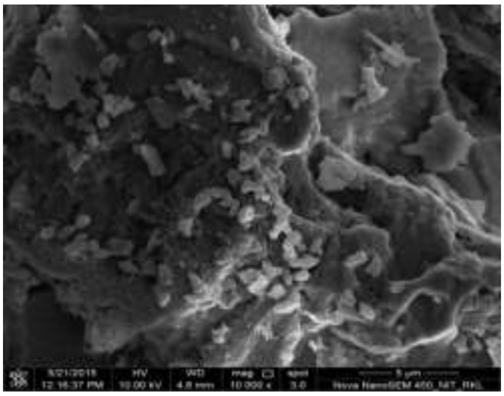
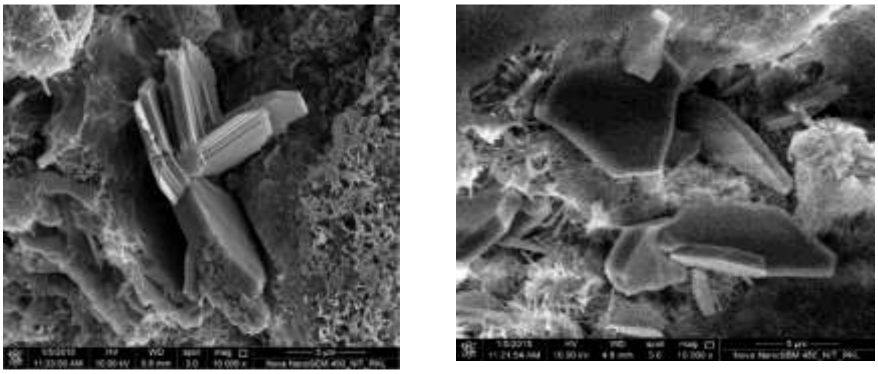
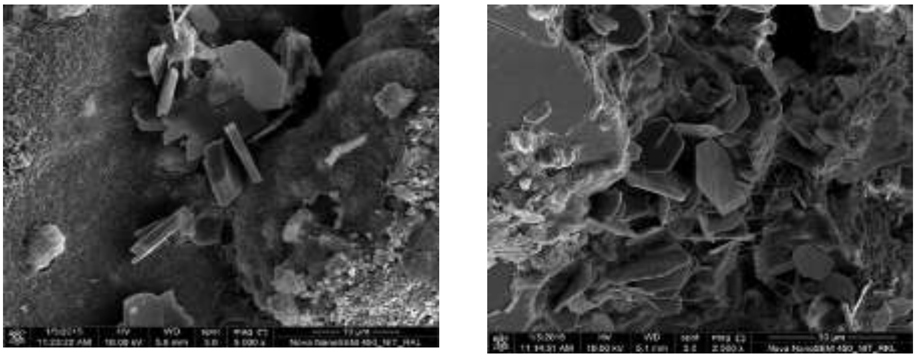


Figure 3.23: FESEM image showing bacteria spreading over calcite crystals



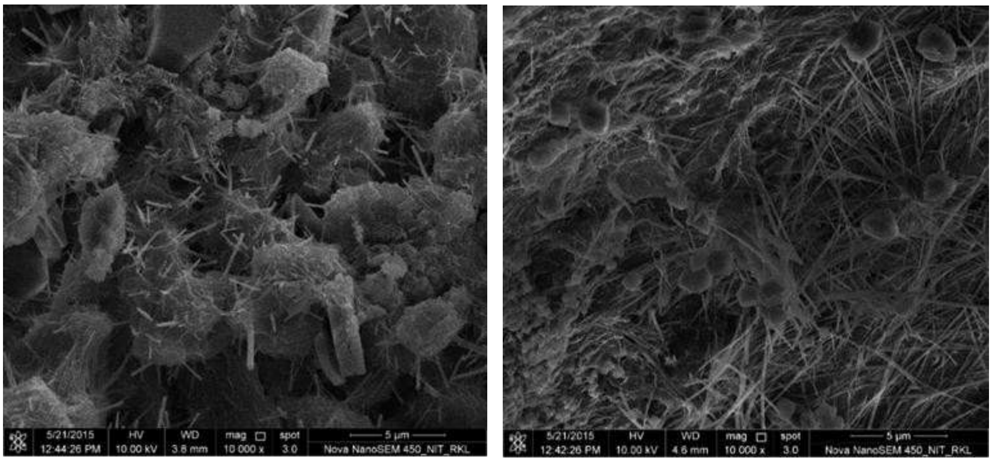
Control specimen Bacterial specimen B4

Figure 3.24: FESEM image of cubes after 7-day curing

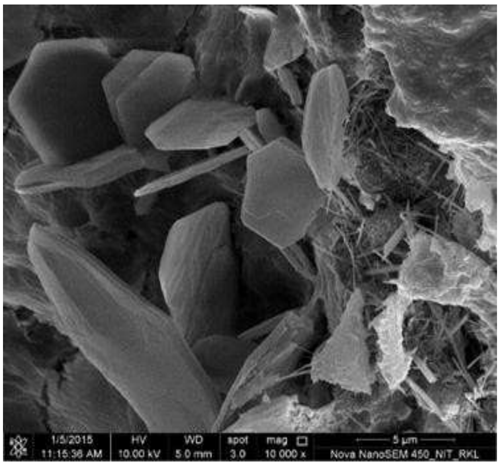


Control specimen Bacterial specimen B4

Figure 3.25: FESEM images of cubes after 28-day curing



(a) After 7 days curing (b) After 14 days curing



(c) After 28 days curing Figure 3.26:

FESEM images of cubes

## 4.1 Conclusions

The objectives of the present work were to investigate the relationship of w/c ratio with compressive strength of RCA concrete considering age and number of recycling and to study the behavior of RCA concrete about the capillary water absorption, drying shrinkage, air content, flexural strength and tensile splitting strength. Experiments are conducted to study the above-mentioned aspects and following are the major conclusions from the present study.

It is well known that the properties of concrete made with RCA are inferior to the normal concrete. The first part of this chapter discussed the aspects such as number of recycling and the age of the RCA, and its effects on the mechanical properties of RCA concrete. Second part of this chapter presented the experimental results of enhancement of mechanical properties of RCA concrete using two types of ureolytic bacteria. The last part of this chapter investigated properties of cement and cement mortar incorporating bacteria. The salient conclusions from each part of the study are summarized below.

Behavior of RCA concrete

- The compressive strength of concrete prepared from older (2 years, RC-2) aggregate is found to be lower in comparison to RC1 (1-year-old). The reduction of compressive strength was about 6%. The reduction in compressive strength was probably higher amount of adhered porous mortar which reduces the strength of aggregate significantly.
- The strength of NCA concrete is higher than RCA concrete at lower w/c ratios. However, a reversal of this trend, i.e., RCA concrete shows higher compressive strength than NCA concrete after a particular threshold *w/c* ratio. The present study found that the RCA concrete requires a threshold minimum quantity of water depending upon the parent adhered mortar to contribute to the strength. This minimum quantity of water in terms of *w/c* ratio for RC-1 and RC-2 was about 0.37 and 0.42 respectively. In order to obtain higher compressive strength for RCA (than NCA), *w/c* ratio should be higher than the above-mentioned minimum limits.
- The compressive strength of concrete after successive (two times) recycling, N2-RC-1 is less than that of RC-1 (one time) and the decrease in strength of N2-RC-1 is about 2% compared to that of RC-1. N2-RC-1 shows higher compressive strength than NCA for w/c ratios higher than 0.42. The successive recycling reduces the quality of the adhered mortar, and this may be reason for the decrease in strength after further recycling.
- Capillary water absorptions of RC-1 and RC-2 concrete are about 11% and 76% more compared to that of NCA. It is found that the capillary water absorption of N2-RC-1 is about 9 times larger than both RC-1 and NCA concrete. This abrupt increase of water absorption behavior of N2-RC-1 leads to conclude that successive recycling may yield poor quality of aggregates that may not suit for concrete.
- The drying shrinkage strain of RC-1 and RC-2 are about 1.9 and 2.6 times more than that of NCA concrete respectively whereas that of successive recycled concrete, N2-RC-1 is about 1.2 times more than RC-1, which shows that successive recycling increases the drying shrinkage strain of concrete.
- Air contents of RC-2 and N2-RC-1 are found to be higher than that of NCA and RC-1.

- While the decrease in splitting tensile strength of RC-2 concrete compared to RC-1 is in the range of 14-28%, the same in flexural strength is in the range of 6% to 21%. The successive recycling reduces the splitting tensile strength and flexural strength by 6% and 12% respectively.

Enhancement of RCA concrete using bacteria

- Properties of RCA concrete such as compressive strength, capillary water absorption and drying shrinkage are improved by the addition of *B. subtilis* bacteria.
- The compressive strength of RCA concrete at 28 days is found to be increased by 20.93% for *B. subtilis* (B-3a) and 35.87% for *B. sphaericus* (B-3b) with respect to RCA control mix at an optimum cell concentration of $10^6$ cells/ml.
- Both bacillus bacteria play vital roles for increment in compressive strength of RCA concrete due to the calcium carbonate precipitation in the pores. Calcium carbonate precipitation by both bacteria in the form of calcite is confirmed through microstructure analysis using SEM, EDX and XRD.
- Both bacteria decrease the drying shrinkage strain and capillary water absorption of RCA concrete and thereby enhances the durability. This can be attributed to denser RCA concrete formed by bacterial activity.
- Air content in bacterial RCA concretes are found to be slightly more than control mix RCA concrete during the initial stage of mixing. This can be reduced perhaps by increasing the mixing time to allow the extra air to go out of the concrete mix. Generalised conclusions on this aspect require further research.

Effect of bacteria on cement and cement mortar

- *B. sphaericus* bacteria is found to be not altering the setting times of the cement paste.
- It is observed that *B. sphaericus* can survive in alkaline concrete like environment and can produce Calcium Carbonate. Addition of bacteria alone cannot improve the properties of concrete/cement mortar. Ureolytic bacteria require urea and a source of calcium to produce $CaCO_3$.
- Compressive strength (at 7-day and at 28-day) of mortar cube is found to be increasing with the increase of bacteria cell concentration up to $10^7$ cells/ml.

However, it is found that further increase of bacteria concentration reduces the compressive strength of cement mortar.

- The optimum doses of bacteria is found to be $10^7$ cells/ml and the corresponding increments of average compressive strength are observed to be 58% (at 7-day) and 23% (at 28-day).
- Curing solution alone does not have any impact on the compressive strength of concrete.
- Sorptivity coefficient decreases as the concentration of bacteria increases which increases the durability of specimen. The minimum sorptivity coefficient is obtained for a cell concentration of $10^7$ cells/ml.
- The XRD study shows that the presence of more calcite peaks in bacterial mortar sample at 28 days than the control specimen.
- The morphology of the bacterial calcite is studied by FESEM. The direct involvement of bacteria in calcite production can be inferred by rod shaped impressions which is consistent with the dimensions of the bacteria on the calcite crystals.

## 4.2 Future Scope

The following are the scope for the extension of the present work:

1. The present study can be extended to develop the design code provisions required for RCA concrete in line with that of normal concrete.
2. The present study considered RCA concrete having two ages, one year and two years. This study can be extended to consider much older demolished concrete to represent more realistic situations.
3. This study can be extended to propose stress versus strain relationship of the RCA concrete considering age and number of recycling as different parameters.
4. The stress versus strain relationship of the RCA concrete incorporating bacteria concrete is not available in literature. This study can be continued in this direction.
5. The present study used SF and FA from a single source. The present study can be extended to develop the variability descriptions among various sources.
6. This study can be extended to make the bacterial concrete to more commercial friendly.
7. The cost benefit analysis for the use of recycled materials can be studied.
8. A systematic guideline to design sustainable concrete mix using RCA/SF/FA or mineral precipitating bacteria can be arrived at through specific studies for each of these materials separately.

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